GaN Systems

TRANSFORMING THE WORLD

WITH SMALLER, LOWER COST, MORE EFFICIENT POWER ELECTRONICS

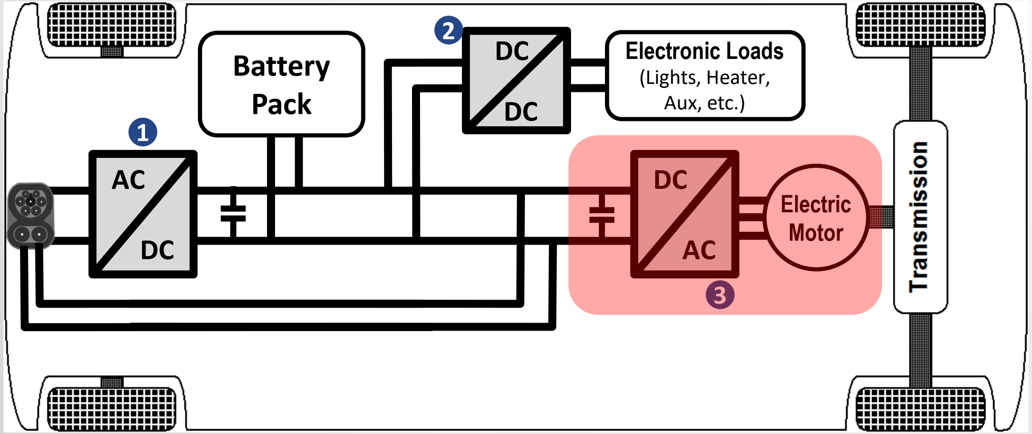
The value of GaN HEMTs in 800V and above applications

GaN Systems University of Alberta

Content

- GaN/Si IGBT based Hybrid T-Type Inverter for Automotive Application
- GaN/Si IGBT based Hybrid ANPC Inverter for Industrial Applications

Opportunities of GaN HEMTs in 10kHz Traction Inverters



Modes	City	High way	Top speed	Accel-erating
% of time	45%	40%	10%	5%
Load	10%	20%	7%	100%

Typical Traction Inverter mission profile

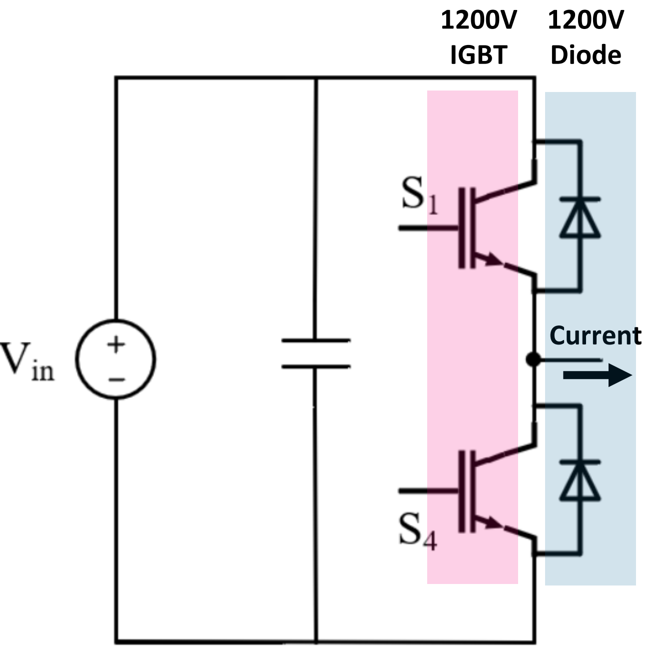
Today's Focus

- On-Board Charger 1
- DC/DC Converter 2
- Traction Inverter 3
  - 400V inverter
  - 800V inverter

GaN is a game changer:

- Switching loss is dominant at partial load even @10kHz
- Increased range and/or lower battery costs
  - Increased Range → Fewer lifetime charge cycles
  - Optimized Price/Performance ratio – for discussion

Conventional Two level Phase Leg – and Limitations



Two-level phase leg

Phase Current	Initial Vector	Final Vector	Con Loss Distribution	SW Loss Distribution	Conditions
+	P	N	S_{11} and S_{21}	$E_{off}(S_{11})$	Inverter(Active)
+	N	P	S_{11} and S_{21}	$E_{on}(S_{11})$	Inverter(Active)
-	P	N	S_{11} and S_{21}	$E_{on}(S_{21})$	Inverter(reactive), Regeneration
-	N	P	S_{11} and S_{21}	$E_{off}(S_{21})$	Inverter(reactive), Regeneration

Limitations:

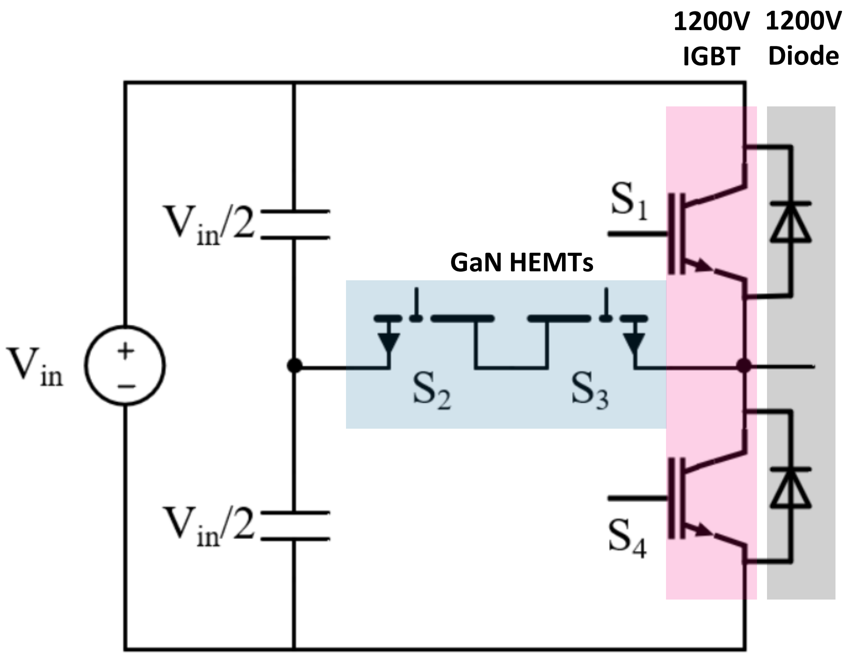
- All the switching transitions happen at higher V_{BUS} voltage
- Silicon Reverse Recovery losses are very high

Under Consideration for higher efficiency:

- SiC MOSFET + SiC Diode to reduce losses
- 1200V GaN not ready for production

Same Topology, better devices?

Proposed Solution: T-type Two/Three-level Phase Leg



Three-level Si/GaN Hybrid phase leg

Solution includes:

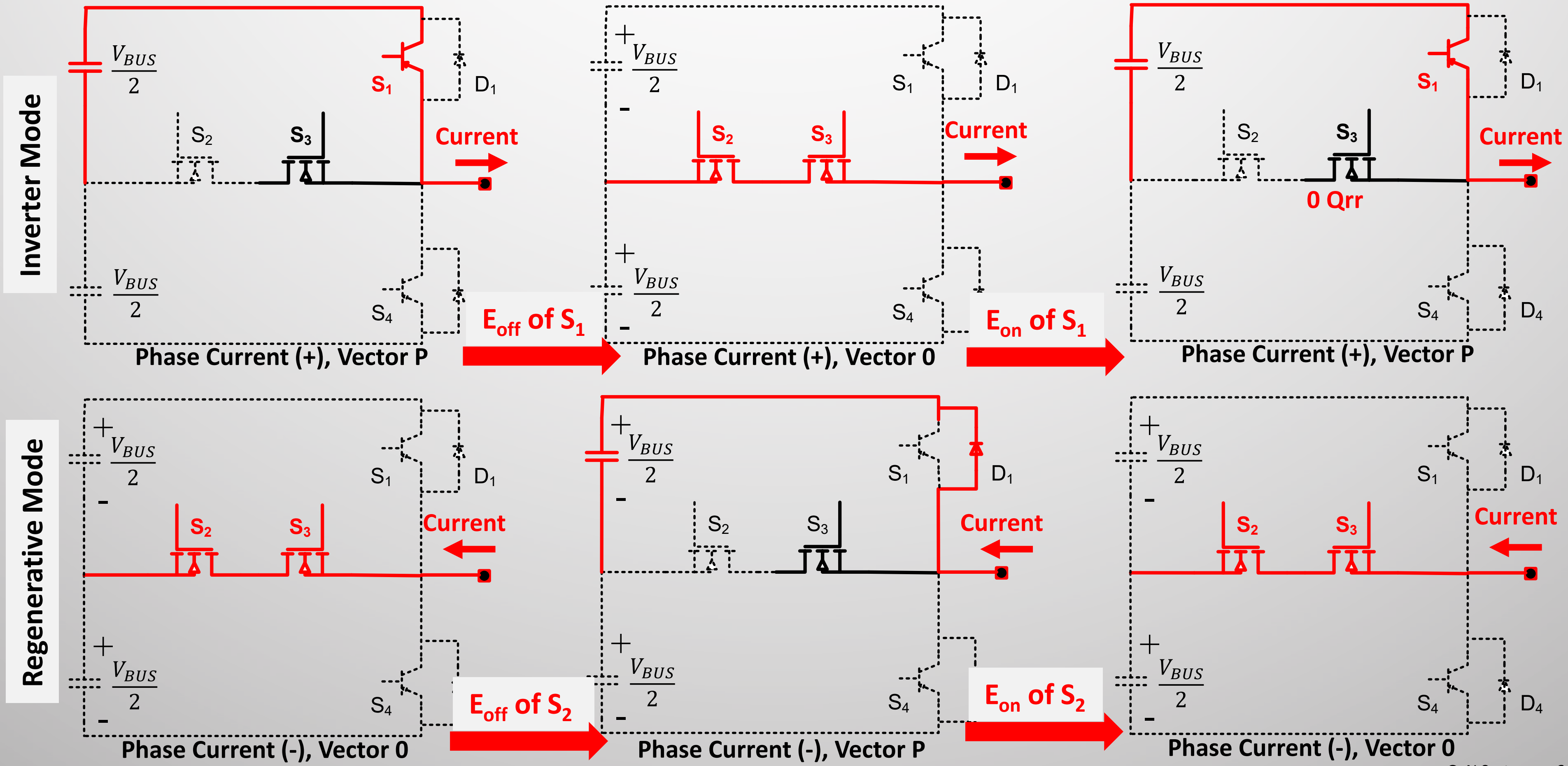
- Fully rated IGBT switches (1200V, 100% current)
- No SiC diodes required
- 2 Additional GaN E-HEMTs rated at
  - *1/3* full load current
  - *1/2* Bus voltage (650V)
- Neutral point clamped battery solution
  - Hard wired simplest, control algorithm possible

Improvements in Efficiency come from 3L operation:

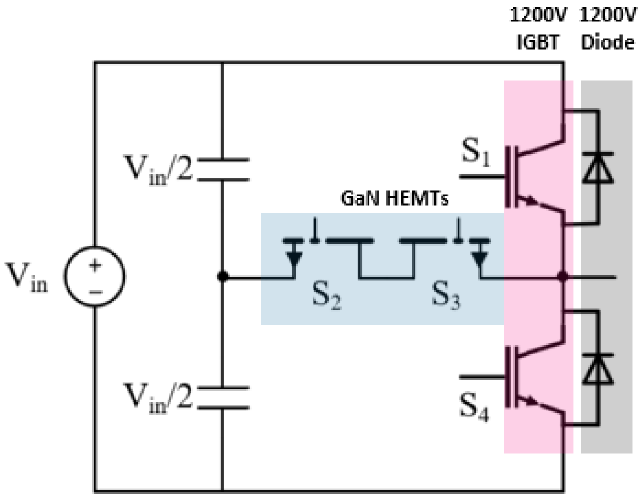
- Vbus/2 Switching Transitions (as compared to Vbus)
- Inverter Mode: IGBT hard-switching → no Qrr in GaN
- Regen Mode: GaN hard-switching → very low Eon/Eoff

Proven Topology, BEST devices for the job

Operating Principles



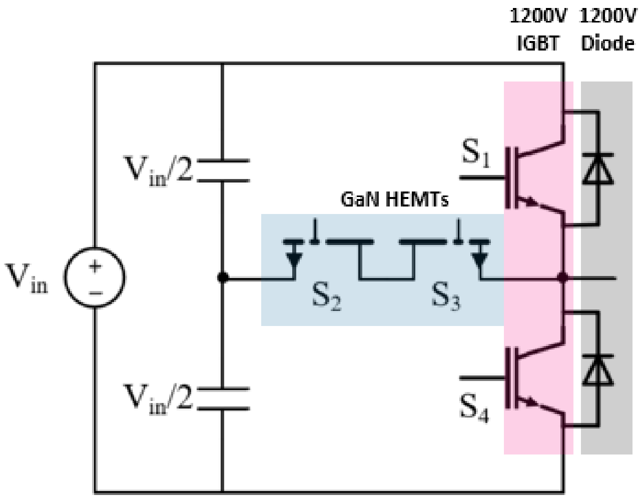
Operation Rule of The T-type Three-level Phase Leg



Three-level Si/GaN Hybrid phase leg

Phase Current	Initial Vector	Final Vector	Con Loss Distribution	SW Loss Distribution	Conditions
+	P	0	S_1 and S_2 , S_3	$E_{off}(S_1)$	Inverter(Active)
+	0	P	S_1 and S_2 , S_3	$E_{on}(S_1)$	Inverter(Active)
-	P	0	S_1 and S_2 , S_3	$E_{on}(S_2)$	Inverter(reactive), Regeneration
-	0	P	S_1 and S_2 , S_3	$E_{off}(S_2)$	Inverter(reactive), Regeneration
-	N	0	S_4 and S_2 , S_3	$E_{off}(S_4)$	Inverter(Active)
-	0	N	S_4 and S_2 , S_3	$E_{on}(S_4)$	Inverter(Active)
+	N	0	S_4 and S_2 , S_3	$E_{on}(S_3)$	Inverter(reactive), Regeneration
+	0	N	S_4 and S_2 , S_3	$E_{off}(S_3)$	Inverter(reactive), Regeneration

Fast-Prototype of Si/GaN Hybrid T-type Phase-Leg



Main Switches (S_1, S_2): IKQ50N120CT2

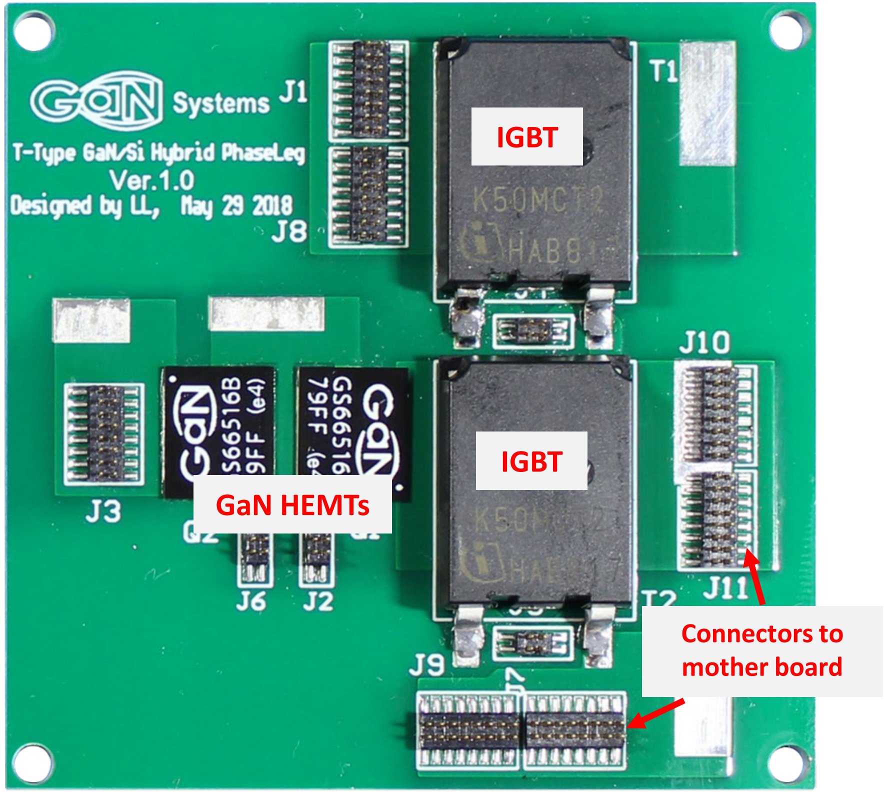
- Infineon, 1200V/50A IGBT with fast recovery anti-paralleled diode
- Intended for Inverter/Vehicle Applications
- To-247 Package

Neutral Clamping Leg (S_2, S_3): GS66516B

- GaN Systems, 650V/25mOhm GaN HEMT
- GaN^{PX} package

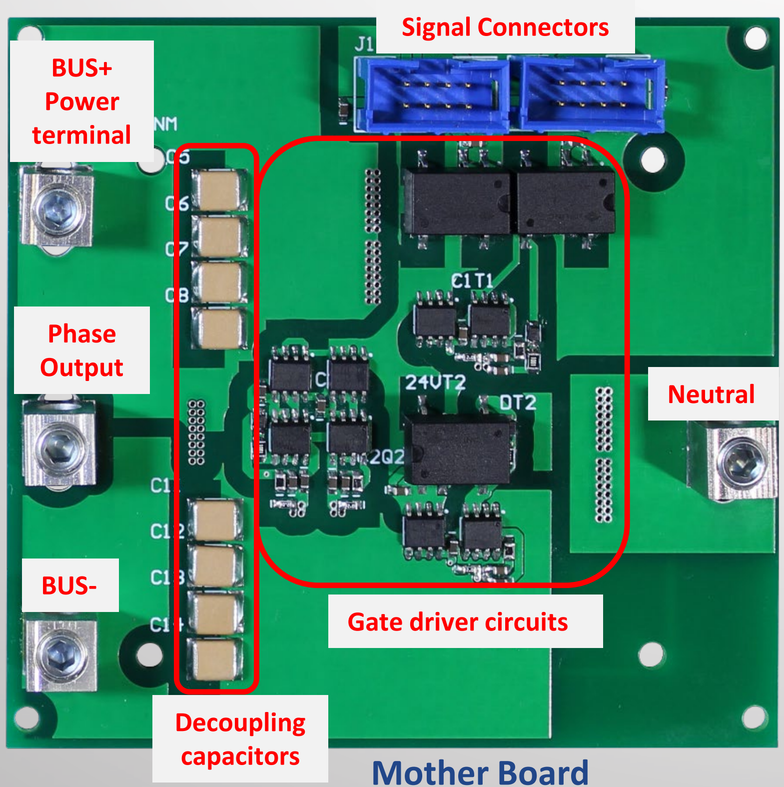
Substrate: Insulated Metal Core Substrate(IMS)

There are no capacitors/resistors on power board

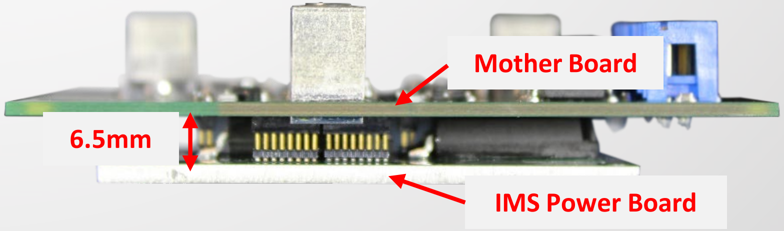


IMS Power Board

Fast-Prototype of Si/GaN Hybrid T-type Phase-Leg

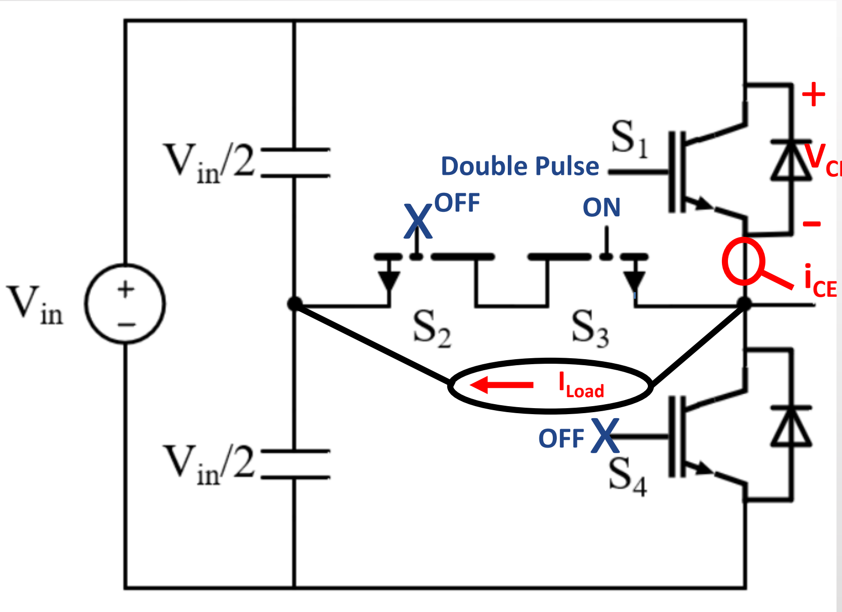


Mother Board



- The mother board is stacked on the top of IMS power board.
- The distance between the mother board and the IMS power board is 6.5mm.

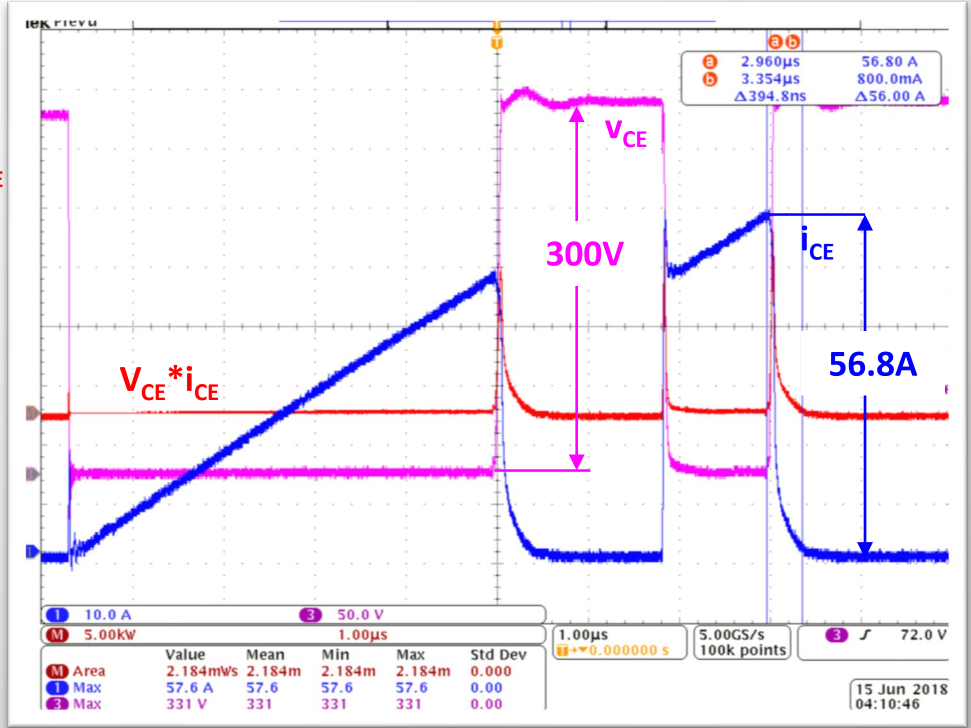
Double Pulse Test



Measurement setup:

V_{CE} - Isolated Probe, THDP0200

I_{CE} - Rogowski Coil, CWTUM/1/B

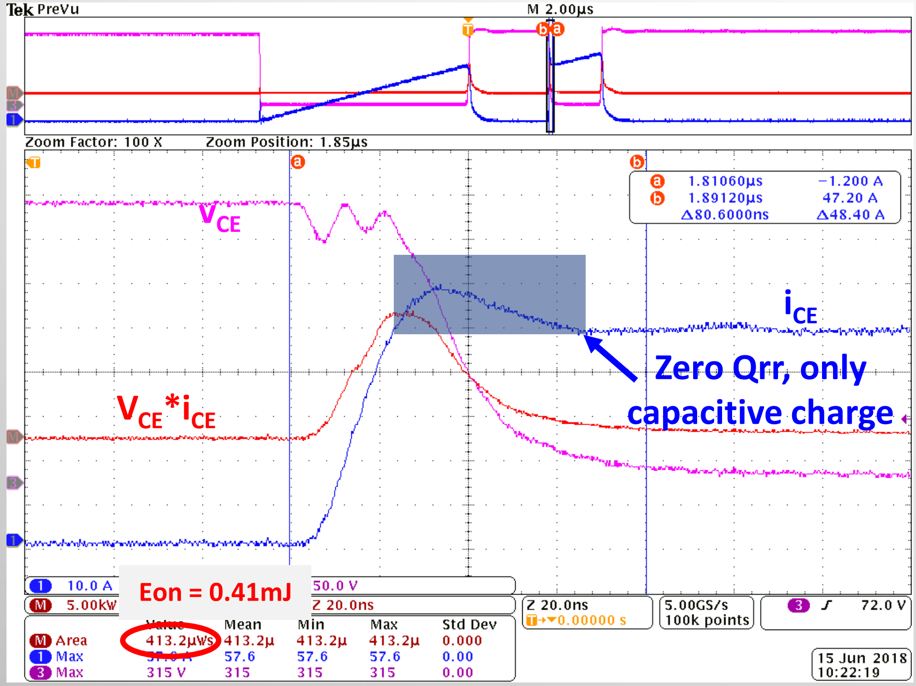


Double Pulse Test Waveform @ V_{BUS}=600V, I_{load}=50A

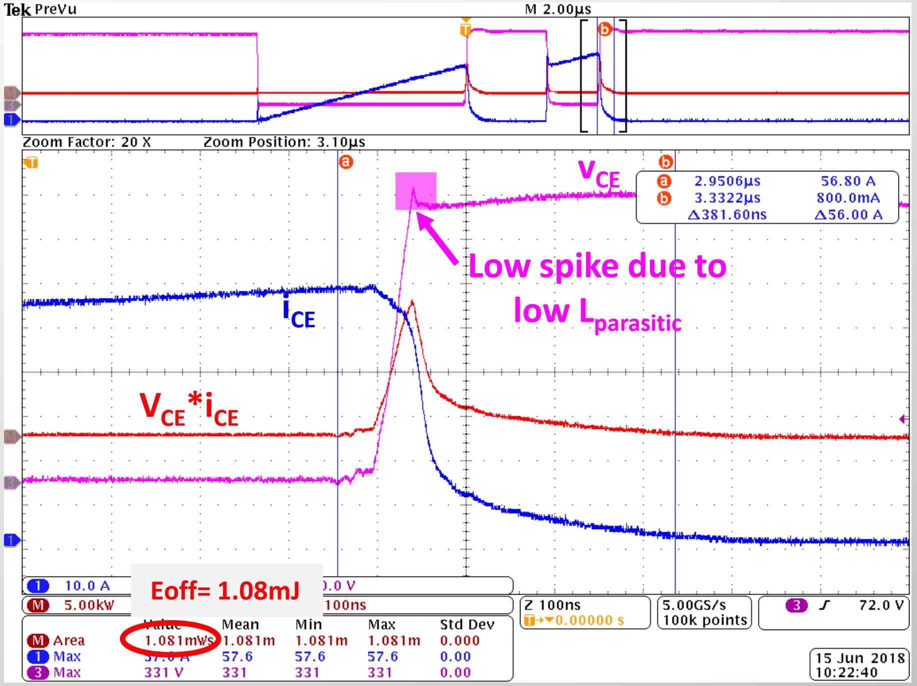
Double Pulse Test Waveforms @VBUS=600V, ILoad= 50A

GaN Systems

Conditions: IGBTs (R_G=2 Ohm, V_{GE}=15V/-9V), GaN HEMTs (R_G=2Ohm, V_{GS}=6V/-6V)



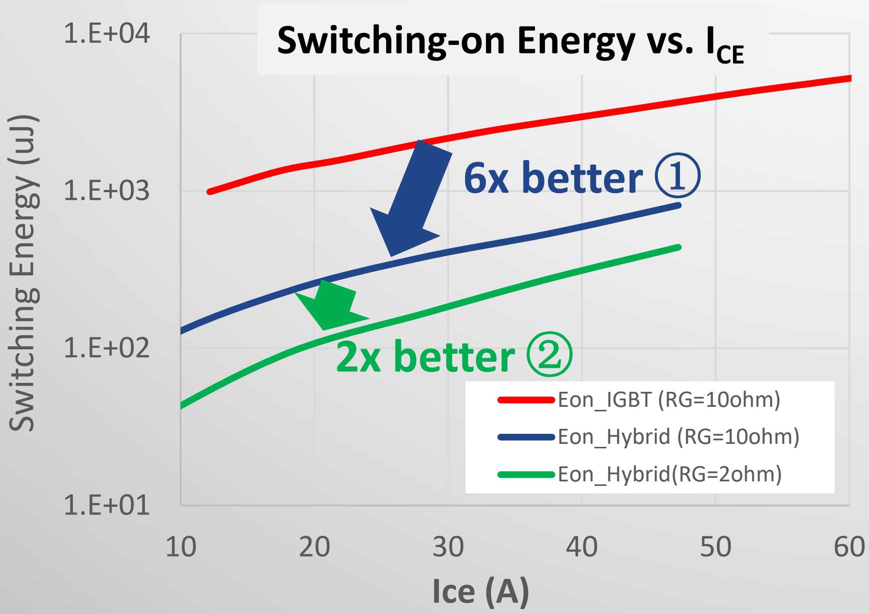
Switching-on Waveform @ V_{BUS}=600V, I_{load}=47.2A

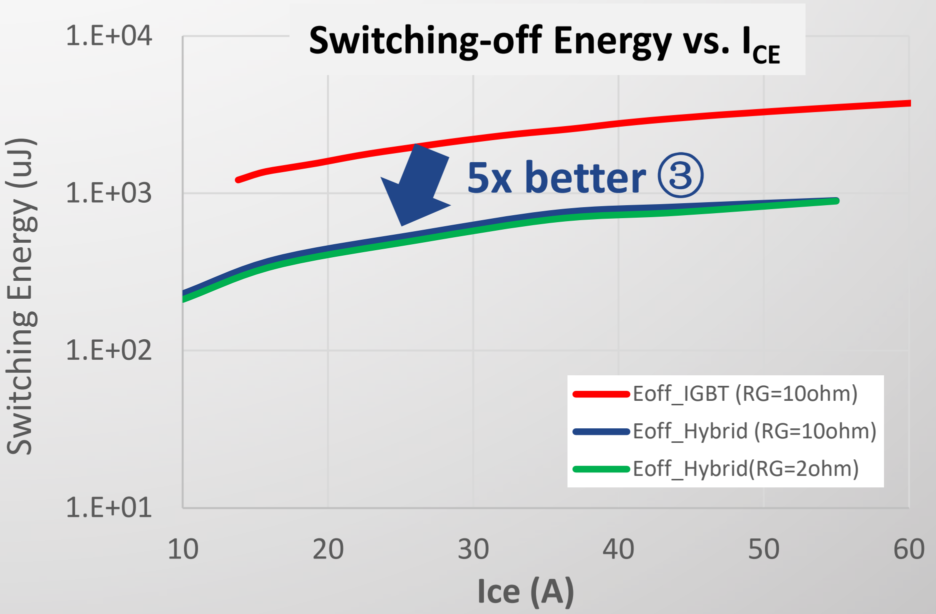


Switching-off Waveform @ V_{BUS}=600V, I_{load}=56.8A

Switching Energy Comparison

Conditions: IGBTs (R_G=2 Ohm, V_{GE}=15V/-9V), GaN HEMTs (R_G=2Ohm, V_{GS}=6V/-6V), T_J= 25℃ ; the switching energy of IGBT is derived from datasheet of IKQ50N120CT2 @25℃





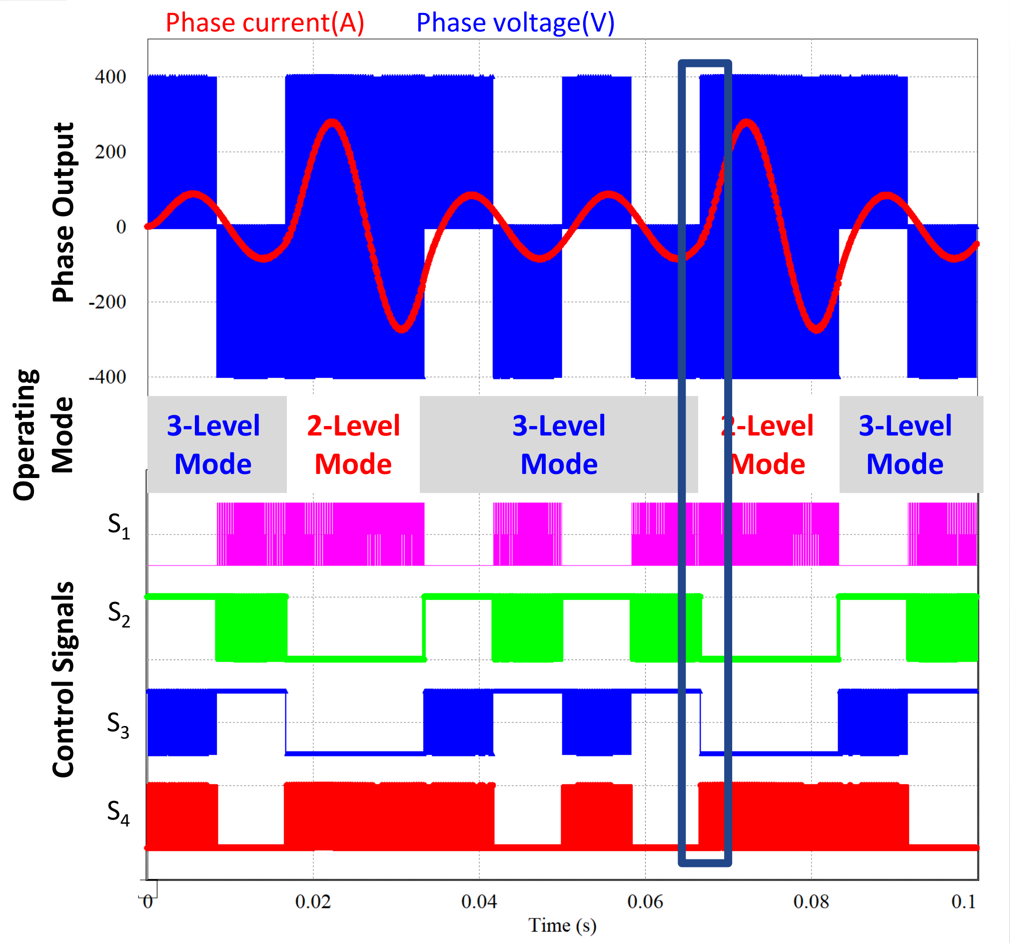
The cause of enhancement:

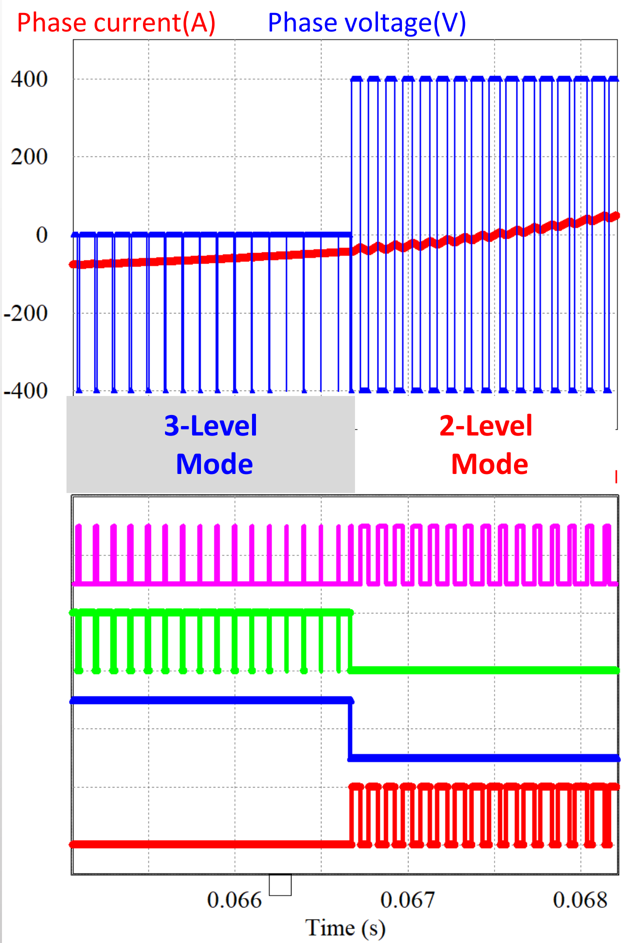
①: **Zero Qrr** of GaN HEMTs, **halved voltage stress** due to three-level configuration

②: More aggressive gate driver parameters enabled by **zero Qrr** of GaN HEMTs

③: **halved voltage stress**, and **lower Eoss** (only 1/8 of conventional two-level configuration)

Simulation of Operating Rules across mission profile





Transistor technology comparison for Traction Inverters

Objective:
- Compare Semiconductor solutions for Traction Inverters
- For modeling purposes, use the mission profile shown

Modes	City	High way	Top speed	Accel-erating	Regen-eration
% of time	45%	40%	10%	5%	Braking
Load	10%	20%	7%	100%	30%

Typical Traction Inverter mission profile

Case 1: “800V, 150kW”
- 10kHz inverter
- Input conditions below:
  Battery Voltage Range: 500V - 870V
  System Power: 150kW
  Motor Voltage: 400Vac Phase-Phase
- Compare **3** possible solutions
  - IGBT solution
  - SiC solution
  - T-Type hybrid – IGBT + GaN Solution

Case 2: “400V, 100kW”
- 10kHz inverter
- Input conditions below:
  Battery Voltage Range: 220V – 460V
  System Power: 100kW
  Motor Voltage: 160Vac Phase-Phase
- Compare **4** possible solutions
  - IGBT solution
  - SiC solution
  - T-Type hybrid – IGBT + GaN Solution
  - Gan Solution (here 650V GaN could be used)

Electrical Performance Comparison for ~150 kW Applications

Specs: V_{BUS}=800V, V_{AC}=400VRMS, Rated phase power= 50 kW, I_{PEAK} = ~180A, I_{RMS}=~125A

Modes	City	High way	Top speed	Accel-erating	Regen-eration
% of time	45%	40%	10%	5%	Braking
Load	10%	20%	7%	100%	30%

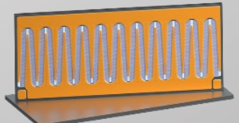
- As the traction inverter is operating at <30% rated current for 90% of the time, this proposal is aimed at improving the efficiency when the load is low (all operating modes other than "Top speed"

Solutions to compare: (note commercial modules used for comparison)

- IGBT - Infineon's latest 1200V/200A half-bridge IGBT module FF200R12KE4
- SiC - Wolfspeed's 1200V/13mOhm SiC module CAS120M12BM2
- Hybrid – same IGBT module with GaN 650V/12mOhm GS-065-120-1-D

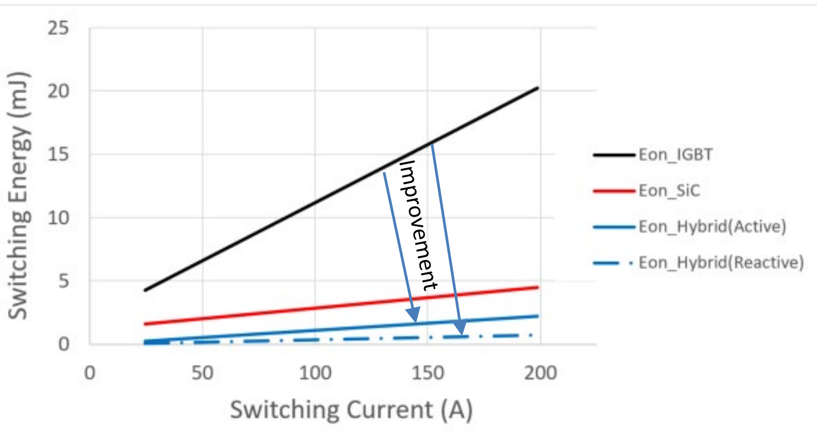

FF400R12KT4P


CAS120M12BM2

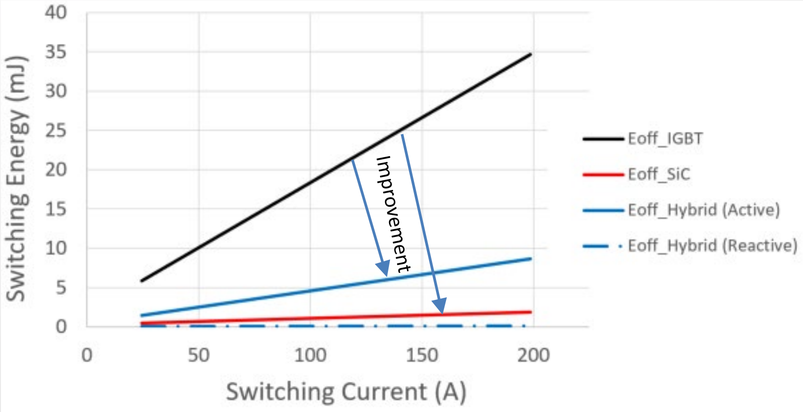

+

GS-065-120-1-D

Hybrid Solution

Switching Loss Comparison



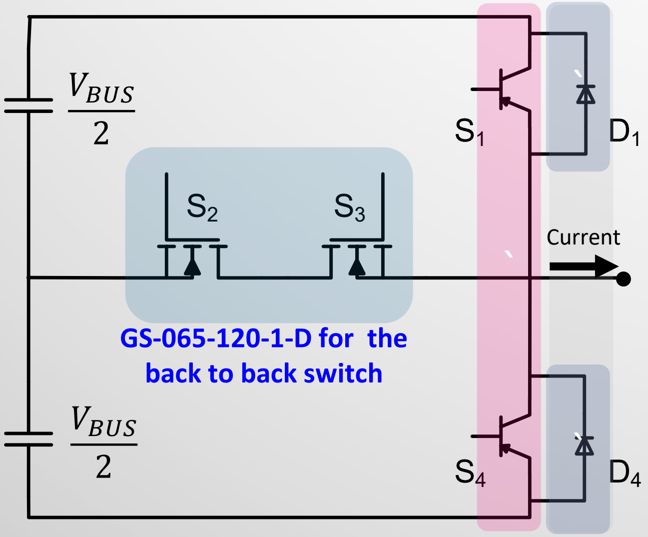
The switching ON energy @V_{BUS}=800V



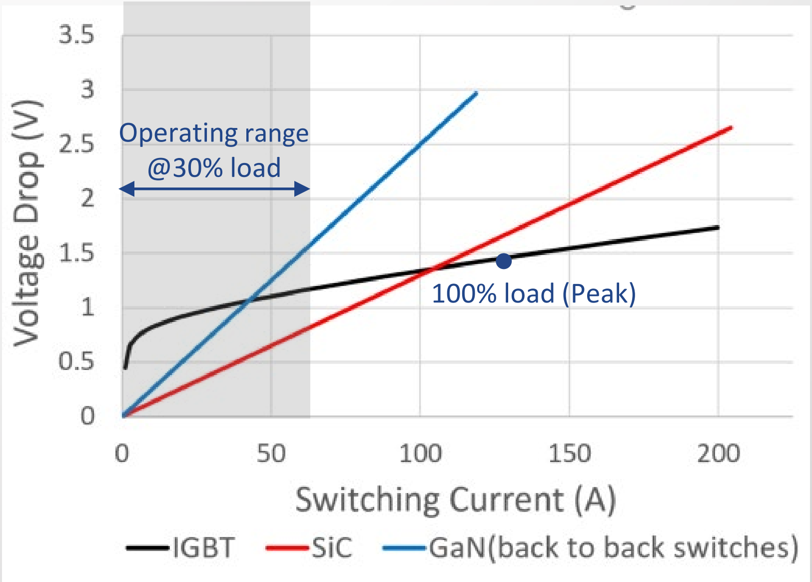
The switching OFF energy @V_{BUS}=800V

Conditions	Improvement
Active (Switching on)	• The voltage stress across IGBT during switching transition is clamped to $V_{BUS}/2$ by GaN. • No reverse recovery and the Low C_{oss} of GaN significantly reduces current overshoot.
Active (Switching off)	• The voltage stress across IGBT during switching transition is clamped to $V_{BUS}/2$ by GaN. • The low C_{oss} of GaN results in a much higher dv/dt and lower loss despite the tail current of IGBT.
Reactive	• The ultra-fast switching transition of GaN results in a low switching on and off loss.

Conduction Loss Comparison



The Hybrid T-type three-level phase leg



Voltage drop vs. conducting current

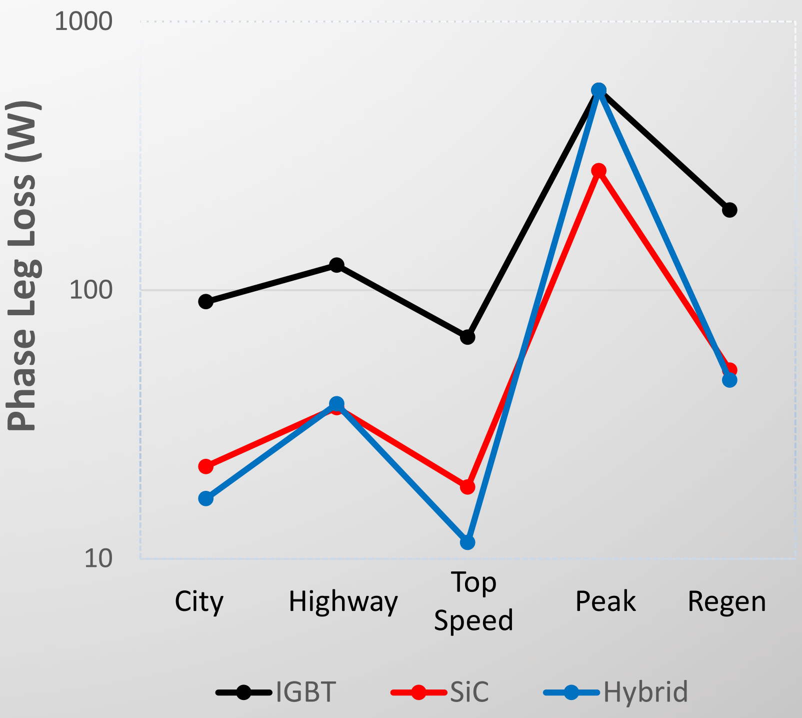
- In most of the operating range of less than 30% load, GaN back-to-back switches contributes less conduction loss than IGBTs – Extending range/Reducing battery for 90% of the mission profile.
- In Peak mode, GaN back-to-back switches are disabled and contribute no loss.

Efficiency Analysis (50kW/phase, 800V/400VAC, 10kHz)

Modes	City	Highway	Top speed	Accelera-ting	Regenera-tion
Percentage of time	45%	40%	10%	5%	Braking
Load	10%	20%	7%	100%	30%

- Weighted average of energy consumption (power loss) across discharge/regen cycle

Device Type	Weighted average loss of Leg (w)	Improvement over IGBT	Current Rating /Relative Cost
IGBT	125	-	100% IGBT
SiC	40	67%	100% SiC
Hybrid (GaN/IGBT)	51	59%	100% IGBT + 33% GaN



Power Loss Comparison

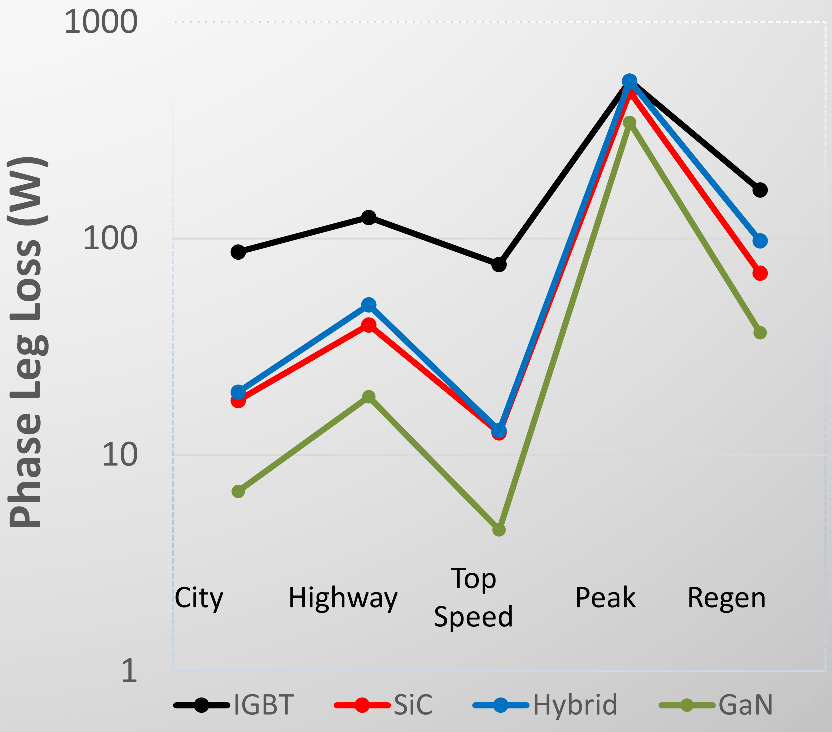
Use GaN 3L operation most efficient when required, use 2L IGBT's for Peak conditions

Efficiency Analysis (33kW/phase, 400V/160VAC, 10kHz)

Modes	City	Highway	Top speed	Accelera-ting	Regenera-tion
Percentage of time	45%	40%	10%	5%	Braking
Load	10%	20%	7%	100%	30%

- Weighted average of energy consumption (power loss) across discharge/regen cycle

Device Type	Weighted average loss of Leg (w)	Improvement over IGBT	Current Rating /Relative Cost
IGBT	123	-	100% IGBT
SiC	49	57.7%	100% SiC
Hybrid (GaN/IGBT)	56	54.2%	100% IGBT + 33% GaN
GaN	28	77.2%	100% GaN



Power Loss Comparison

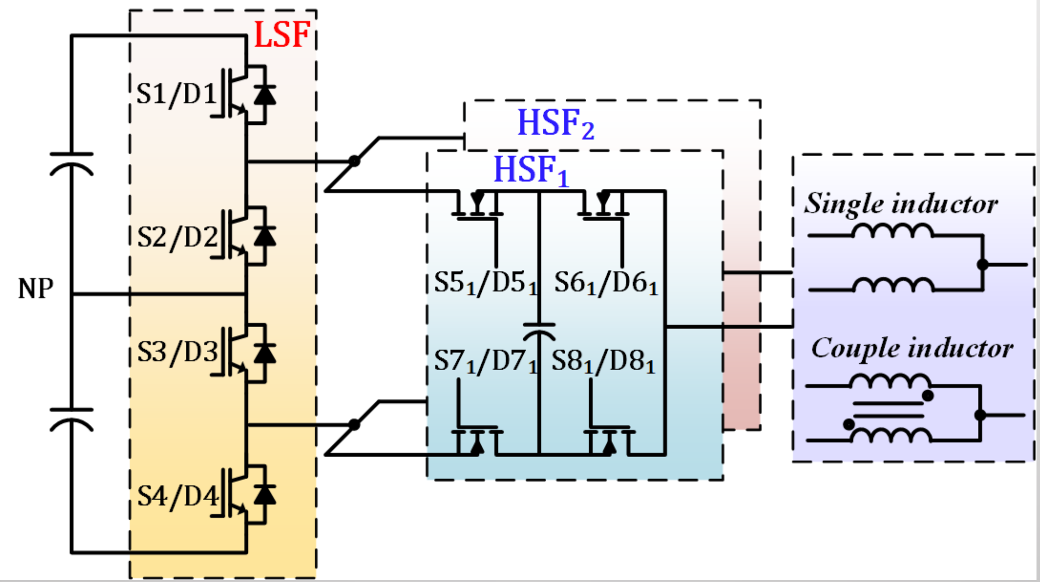
All GaN or Hybrid GaN+IGBT offer best price/performance

Content

- GaN/Si IGBT based Hybrid T-Type Inverter for Automotive Application
- GaN/Si IGBT based Hybrid ANPC Inverter for Industrial Applications

Specs & Topology

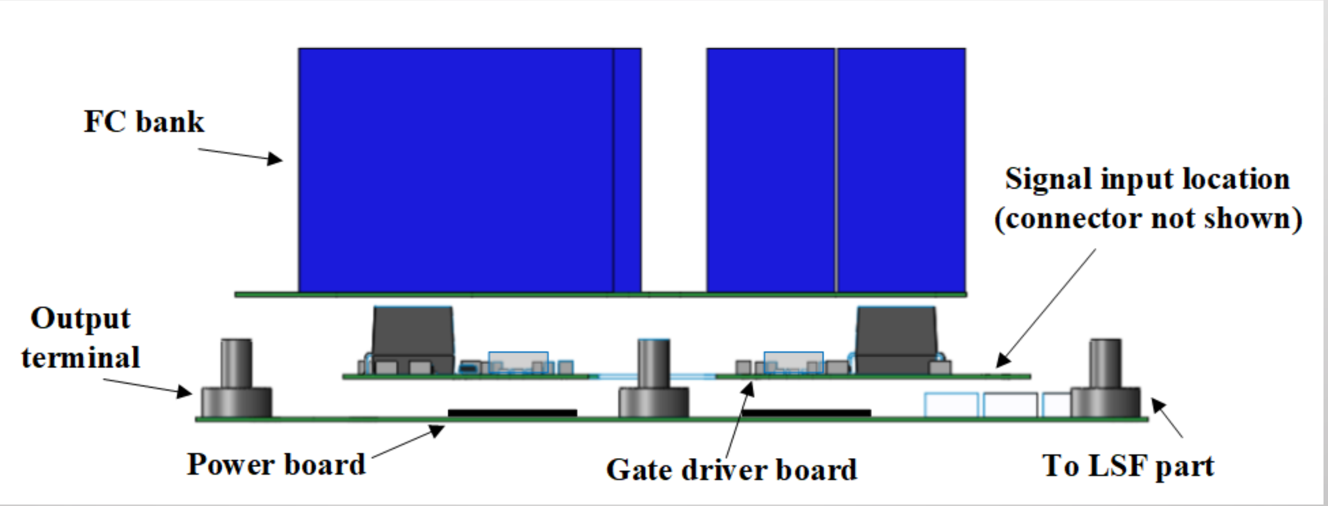
- ~1.5kV DC input, 690Vrms AC output, 70kW
  - Internal-parallelization converter (IPC)
  - Interleaving - nine-level output
- Hybrid Si / WBG design for low cost and improved efficiency



HSF Module Design

❖ GaN based HighSwitching Frequency(HSF) module design

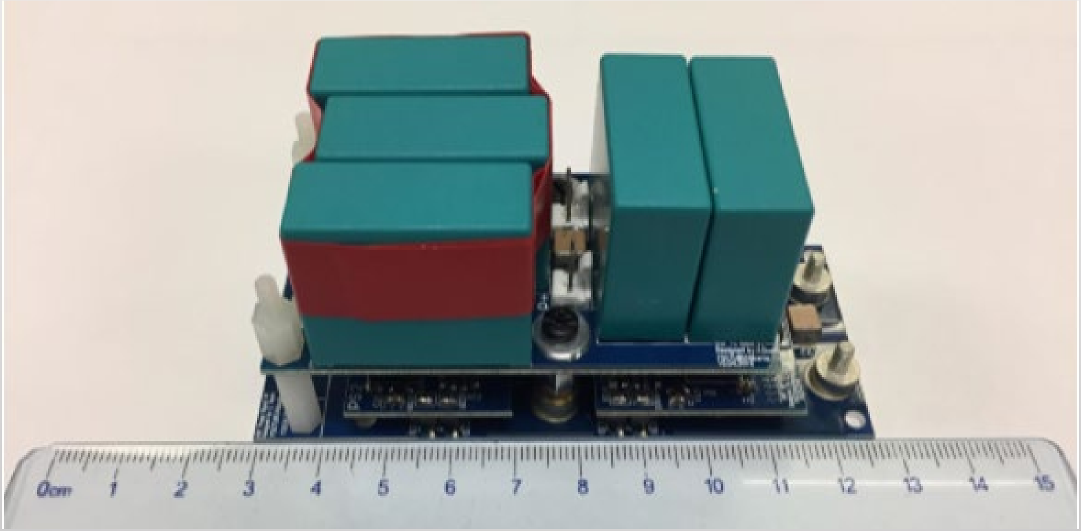
- 30kHz carrier frequency
- Three-layer stack structure



HSF Module Design

❖ **GaN based HSF module design**

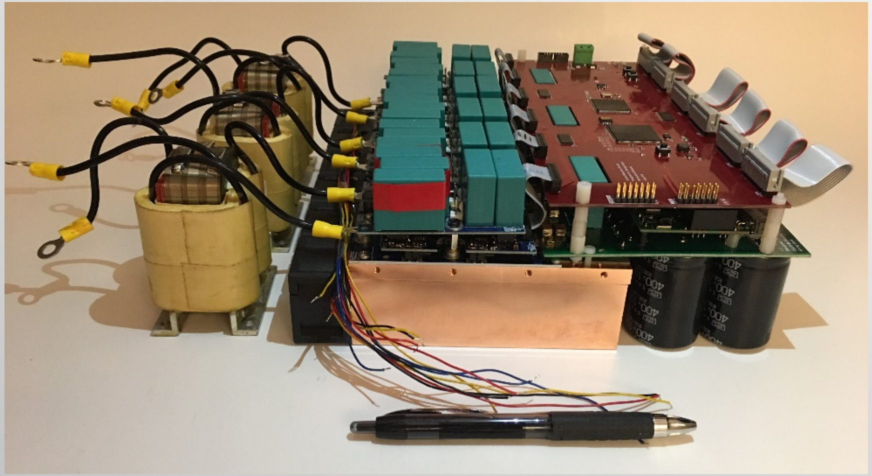
- 50uF (5 x 10uF) flying capacitor bank based on capacitor current rating and voltage ripple constraints



Prototype Construction

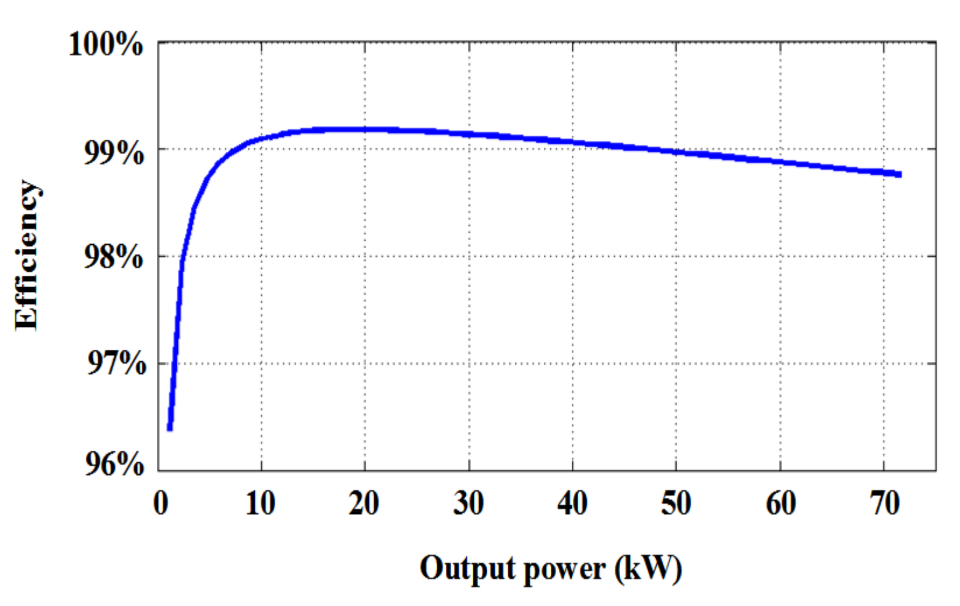
❖ 3D construction

- 240mm x 20.7mm x 88.2mm = 4.38L
- Fans and filter (not shown) less than 1L



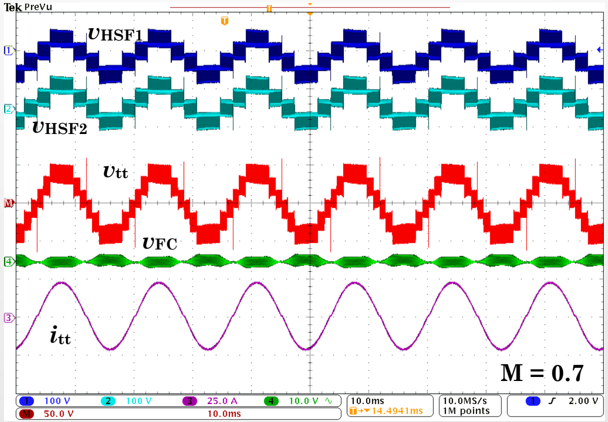
❖ Efficiency Estimation

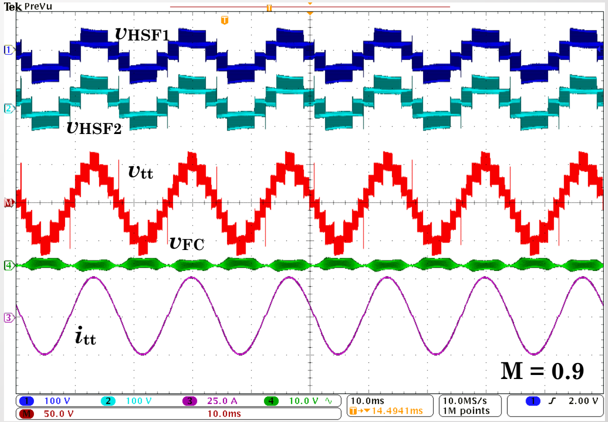
- Peak efficiency - 99.2% with all the auxiliary power supplies included



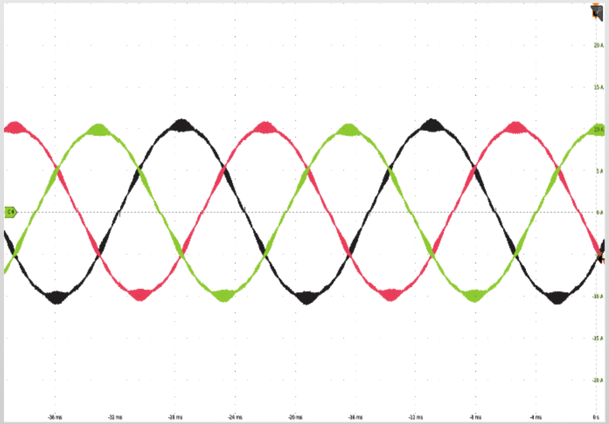
Lab-Scale Experimental Results

- **Single-phase tests**
  - DC voltage 140V, Rload is 2Ω for single phase test and 6Ω for three-phase test

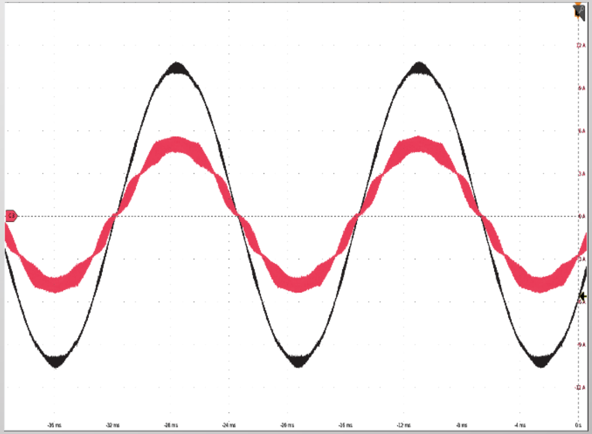




- **Three-phase Test Results**



Three-phase current – coupled inductor



HSF module current vs. total current

Conclusion

- **Hybrid Si / GaN - get the most out of GaN**
- **Power density above 12kW/L**
- **Estimated power/weight ratio around 5kW/kg**
- **Best in class product: 0.5kW/L 1.3kW/kg**

Thank You!

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